Real-time evacuation and Failure mechanism of an oversize soil landslide on 19th July in Yanyuan County, Sichuan Province, China

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Abstract At around 5:40 am on the 19th July, 2018, an oversize soil landslide (the Boli landslide) occurred on the right bank of Taozi Gully, a branch of Jiami River in Taozi Town, Sichuan Province, China. The landslide destroyed 186 houses and about 300 acres of farmland of Boli Village. Real time evacuation was successfully implemented avoiding the casualties from 65 families (281 people) due to the effective warning. Based on visual interpretation of the multi-temporal remote sensing images, field investigation, analysis of the landslide soils and related model, this study tries to reveal the typical characteristics, the cause and failure mechanism of such an oversize soil landslide. A response mode based on the community warning system has been proposed that is simple, effective and scalable in response to such latent disasters in the mountains from this successful real-time evacuation. And more importantly, we look forward to expanding such successful experiences and effective risk mitigation system in order to improve the disaster prevention and reduction capacity of poor mountainous areas.

Keywords Boli landslide • Ancient landslide • Rainfall • Failure mechanism • Real-time evacuation • Sichuan • China

Introduction

At around 5:40 am on 19th July 2018, a catastrophic landslide occurred at Boli Village in Taozi Town, Yanyuan County, Sichuan Province in southwestern China (N27°29′45″, E101°01′25″). It destroyed 186 houses of 65 settlements and about 300 acres of farmland. Damages of roads, ditches, water pipelines and bridges collectively resulted in a direct economic loss of about 13 million RMB in total. Due to the employment of surveillance staff beforehand with unimpeded information communication and the timely launch of the safety plan, the civilians (97 families, 437 people) were evacuated from the disaster area and the casualties from 65 families of 281 people were avoided.

Immediately after the 19th July landslide event, the Government of Sichuan Province launched on-site emergency rescue and disaster relief operations. One day after the disaster, our research team based at the Key Lab of Mountain Hazards and Surface Processes, Chinese Academy of Sciences in Chengdu together with the emergency response team of Sichuan Land and Resources Department reached the site. The corresponding author of this paper (Prof. Ningsheng Chen), being the leader of the on-site expert board, was directly involved in the investigation, in the analysis of the causes of the landslide, in the prevention of secondary disasters and in the collection of the valuable first-hand data.

Since the occurrence of the event, the following research questions have become hot issues under discussion:

(1) What were the typical characteristics and deformation history of the Boli landslide?

(2) What was the cause of the Boli landslide? How did the landslide occur?

(3) How to conduct the real time evacuation if the Boli landslide had not been identified before the occurrence?

(4) What was the internal relationship between real-time evacuation and landslide failure? How to gain further experience from this successful evacuation?

To the best of the knowledge acquired by the research team, this paper presents the possible answers and views to the above questions. During the emergency rescue, a UAV was flown to obtain high-resolution images and produce a digital surface model (DSM). Together with pre-sliding multi-temporal remote sensing images, digital elevation models (DEM) and data from detailed interview, the typical characteristics and deformation history of the landslide and real-time evacuation process have been identified and analyzed. The volume of the landslide was calculated by comparing pre- and post-sliding DEMs. Physical and mechanical parameters of the landslide soils and related model were analyzed to determine the failure mechanism of the Boli landslide.

Data and methods

After the occurrence of Boli landslide, by collecting data from multiple sources and analyzing them with various techniques, this study contains the first complete overview of the landslide event with respect to its geoenvironment conditions, typical characteristics and failure mechanism of the landslide, its deformation history and real-time evacuation. Table 1 and Fig. 1 summarize the data and the general methodology followed in the study with further details as follows:

(1) Visual interpretation based on multi-temporal satellite images

In order to investigate the deformation history of the Boli landslide, two remote-sensing images prior to the landslide were collected and analyzed through visual interpretation. The earliest image dates on November 9th, 2005 from Google Earth, while the most recent image was obtained from the Chinese Gaofen-2 satellite of June 28th, 2018. The ground resolution of the images (0.8 m) is sufficient for the identification of macroscopic deformation indicators, such as macro-cracks and talus (Zhang et al. 2013; Tian et al. 2017).

For acquiring post-sliding data, our research team relied upon the UAV from which the images from certain height were collected at a high-resolution digital orthophoto map (DOM) and a digital surface model (DSM). The image has a ground resolution of 10–15 cm and covers an area of 17.5km^2 (Fig. 4b). The image was compared with the pre-sliding Gaofen-2 satellite image (recorded on June 28th, 2018, Fig.4a) to carry out detailed geomorphic mapping and analyze the geomorphological characteristics of the landslide. Due to the emergency condition, the ground control points to improve the precision of DOM and DSM were set-up by six GPS points.

(2) Volume and depth calculation using pre- and post-sliding DEM

In order to infer the topographic changes and to estimate the landslide volume, the pre-sliding topographic map at 1:50,000 scale was acquired. A pre-sliding DEM (about 1 m accuracy) was generated using this topographic map. The pre-sliding DEM was then compared with the post-sliding UAV DSM (10-15 cm resolution) to calculate the source mass volume and the deposition volume of the landslide using a Cutfill tool on the ArcGIS platform. Simple raster calculation, as the elevation difference between the pre-sliding and post-sliding DEMs, were used to estimate the depth of the landslide material.

(3) Deformation history and real-time evacuation analysis based on detailed interview and photograph of pre- and post-sliding

In order to investigate the deformation history of the Boli landslide, field survey photos and surface fracture data from the local residents and Geological Disaster Technical Supports of Yanyuan County were collected six days before pre-sliding, excluding remote-sensing images. In order to analyze the real-time evacuation process, detailed interviews and real-time evacuation records were processed in the field survey.

(4) Failure mechanism of the Boli landslide using physical and mechanical parameters of the landslide soils and related model

In order to analyze the failure mechanism of the Boli landslide, some landslide soil samples were collected from the field to analyze their physical and mechanical parameters including density, moisture content, liquid limit, plastic limit, cohesive force and angle of internal friction. The SEEP/W software was used to simulate the change of the seepage field of the Boli landslide under rainfall conditions for the confirmation of the cohesive force(C) and the angle of internal friction（φ）of the soil.

Table 1 Summary of the collected data

Data	Resolution	Date	Data source
Before the disaster			
Topographic map	1:50,000	1971	Sichuan Bureau of Surveying Mapping and Geoinformation
Geologic map	1:200,000	1971	Sichuan Geological Survey
Google Earth image		2005.11.09	Google Earth (Landsat-7)
Gaofen-2 image	0.8m	2018.06.28	Chinese satellite Gaofen-2
During the disaster			
Rainfall		2018.05.01-2018.07.18	Yanyuan county and Taozi town meteorological station
Detailed interview and photograph		2018.07.13-2018.07.19	Field investigation
After the disaster			
UAV image	0.15m	2018.07.21	IMHE, CAS
Landslide soils		2018.07.21	Field investigation

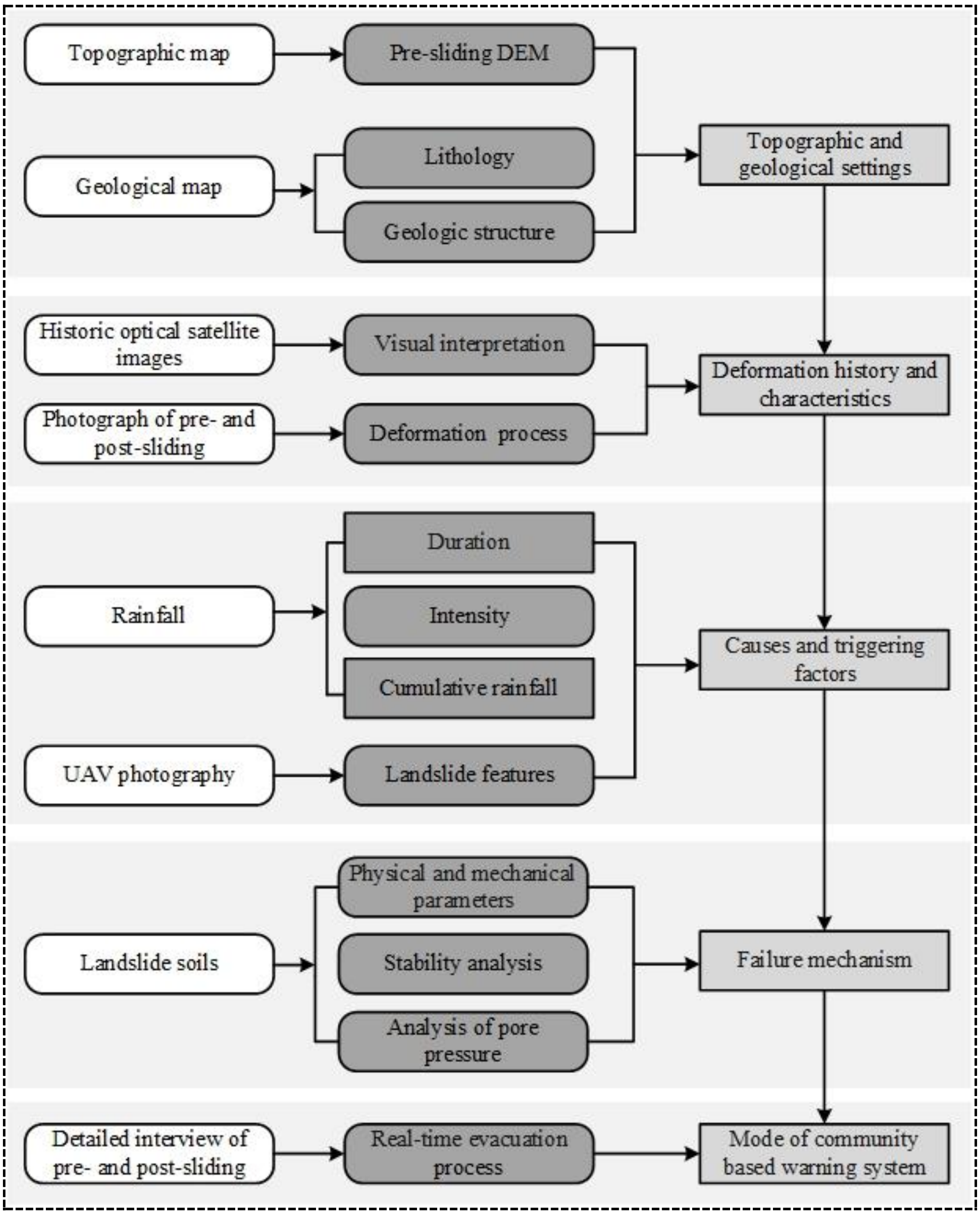

Fig. 1 Flowchart indicating the available data and the general methods

General description of Boli landslide

The landslide occurred on the right bank slope of 7th and 8th groups of Boli Village, Taozi Gully in Taozi Town, Yanyuan County, Sichuan Province (Fig.2). Taozi Gully, a branch of the left bank of Jiami River, with the elevation of the source of the gully at 3346m and that of the outlet at 2062 m, is 15 km in length and 17.5 km^2 in area. This branch has an average gradient of 85‰. For the upper and middle reaches at elevations over 2360 m, their terrains are gentle with a gradient of 70‰ while the rest of the region (the middle and lower reaches) with elevation below that has an average gradient of 149‰. The shape of the gully resembles a strip, with its slope of both sides of the upper and middle reaches greater than 30°. The middle and lower reaches are mainly residential areas and cultivated land as their terrains are relatively gentle.

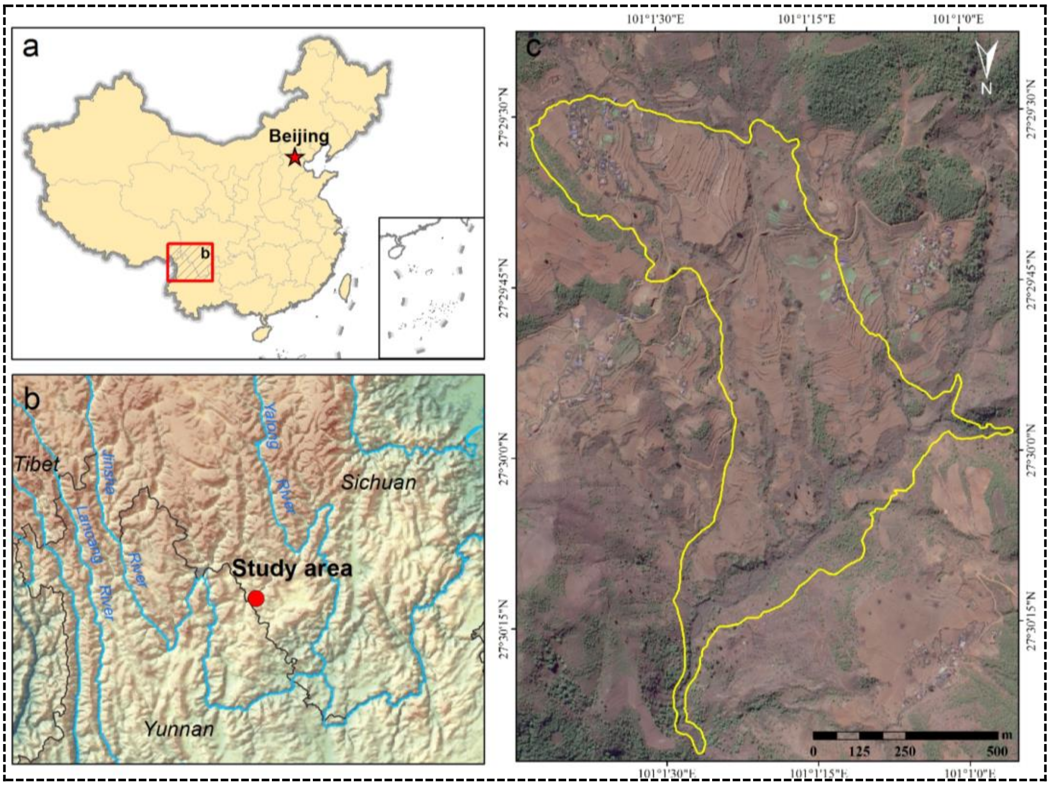

Fig.2 Location of the "7.19" Boli landslide, Yanyuan, China; Pre-sliding image from Chinese Gaofen-2 taken on June 28th, 2018 (c)

The shape of the Boli landslide is elongated in plane (1900m long in north-south direction and 300-400m wide in west-east direction). The main sliding direction of the landslide is between 320° and 345°, with $57\times10^4 m^2$ in area. After the landslide, high-resolution DSM and DOM with 0.12 m precision were obtained by the UAV aerial survey technology, combining with the pre-landslide GDEMDEM (30m precision) from Geospatial Data Cloud site (http://www.gscloud.cn) and remote image from GF-2 (0.8mprecision), the range and volume of the landslide were determined (Fig.2 c and Fig.3 a). Through the Cutfill analysis tool of ARCGIS software, the precise volume was calculated by the difference of pre-and post-landslide DEM (Allstadt 2013). The volume of the Boli landslide is 1800 million cubic meters. The elevation of the shear opening stage is 2362m and the elevation of the back stage which dropped 60min after the landslide process is 2700m, leaving a height difference of 338m. All these features demonstrate that the Boli landslide is an oversize soil landslide.

Typical characteristics of Boli landslide

According to the field investigation and remote sensing analysis (Fig.3), the landslide is paternally divided into the push sliding part in the upper section and the tractive sliding in the lower section. The lower plane's configuration is in a tongue shape, with the elevation of 2500 m at the rear edge and 2362 m at the front edge, causing a difference in height of 170 m(Fig.3 d). The lower part of the landslide is approximately 800 m long in the north-south direction and 300-400 m wide in the west-east direction. The main sliding direction of the lower part is 320°, with $24\times10^4 m^2$ in area and $800\times10^4 m^3$ in volume(Fig.4). The overall slope of the landslide is about 8~45° and the slope of the leading edge is 150m, which is gentle and reversed partially. The rock wall of the trailing edge is partially exposed, and the occurrence is 342/32° as a gentle and consequent slope(Fig.4). The upper plane configuration is also in a tongue shape, with the elevation of 2700 m at the back stage and 2530 m at the front stage, leaving a difference height of 138m (Fig.3 d). The upper part of the landslide is approximately 1200 m long in the north-west direction and 300-400 m wide in the west-east direction. The main sliding direction of the upper part is 345°, with $33\times10^4 m^2$ in area and $1,000\times10^4 m^3$ in volume. The slope of the landslide area is between 25～30°, which is relatively gentle except the escarpment.

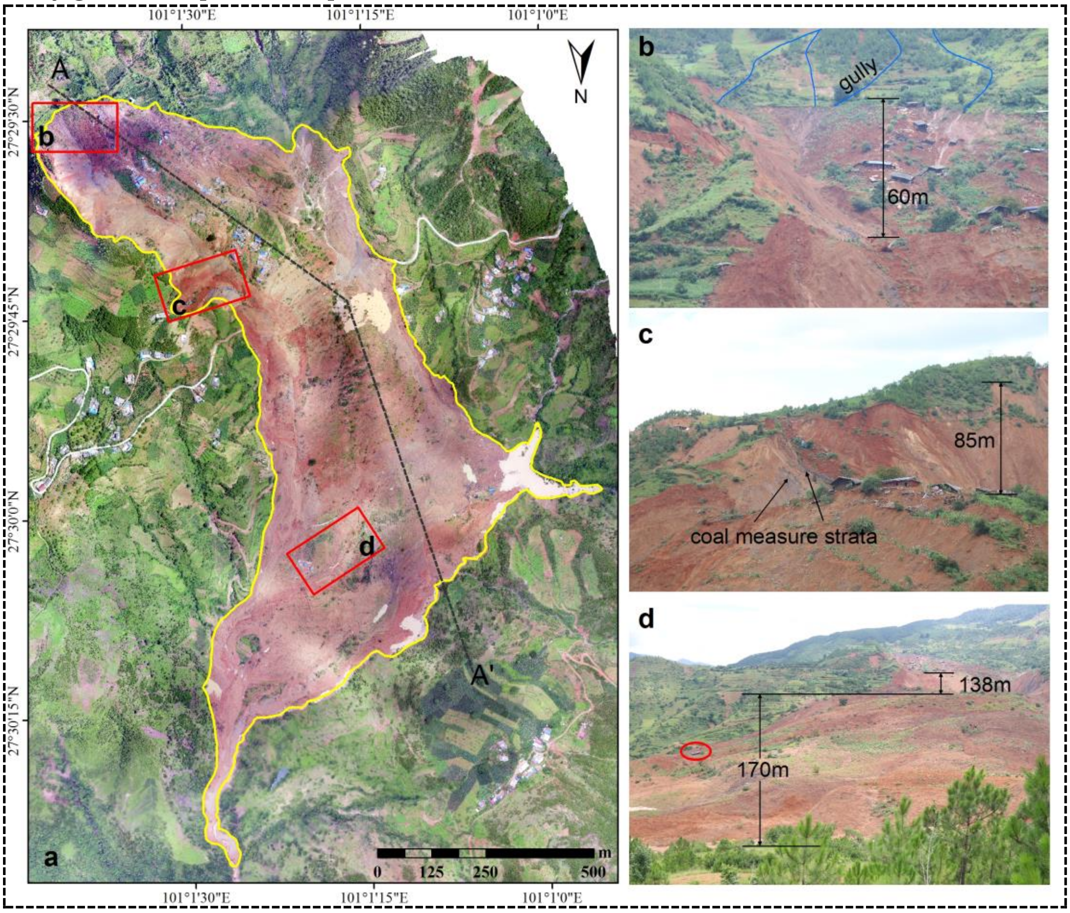

Fig. 3 An overview map of the Boli landslide based on post-sliding image taken by UAV on July 22th, 2018 (a); Field survey photo(b, c, d)

A steep ridge of more than 60m vertically with an extension length of about 150m was formed in the trailing edge of the landslide(Fig.3 b). The vertical steep ridges with height of 35-85 meters were formed in the two sides of the landslide(Fig.3 c). The boundary is straight and the giant scratches are visible. The large-slope sliding area with a gentle slope was formed in the leading edge. The thickness of the deposition is about 170m and the accumulation volume is 800×10^4 m^3. After sliding, the trees and houses in the upper part of the sliding body basically retain their original relative positions and the trees and houses in the middle and lower parts of the sliding body are seriously deformed.

The deformation characteristics of the landslide are that the middle part of the landslide firstly slid and then developed next to the rear part. The displacement of the front portion is large and the rear displacement is small.

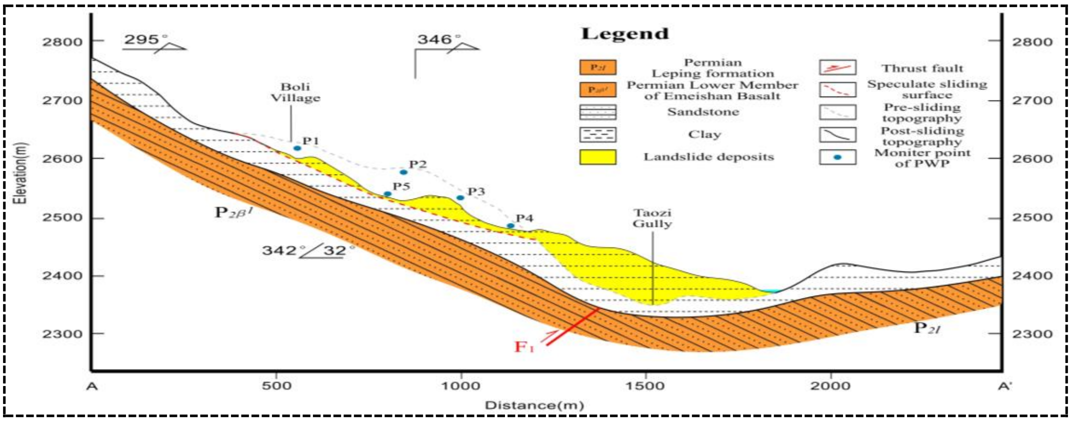

Fig.4 The geological longitudinal profile of the Boli landslide

Deformation history of the Boli landslide

The Boli landslide is formed in two stages of creep deformation and sliding under the excitation of precipitation. The creep deformation stage occurred from July 14th to 18 th (Fig.5). On the 14th, the road and bridge were broken and damaged in Boli Village. On the 15th, some cracks occurred in the front of the landslide, with the crack width ranging from 5to 10cm. On the 16th, obvious dislocation occurred in the middle and front of the landslide, and the maximum height difference of dislocation is 30cm. On the 17th, dislocation and crack occurred in the trailing edge of the landslide, the maximum height difference of dislocation is about 15cm, and the maximum width of crack is 20cm. On the 18th, a large area of slippage occurred in the trailing edge of the landslide with the maximum height difference of 150cm, and the channel water in the middle part of the slope appeared to be interrupted, with groundwater overflew occurring in the front part of the sloping body. Under the action of antecedent-precipitation and runoff yield under excess infiltration, landslides occurred at around 5:40 am on the 19th and formed a disaster (Fig.5). The sliding phase lasted for about tens of seconds. After the landslide occurred, the slip mass was deposited in the Taozi Gully with a length of about 1000m. The rear part of the piled body formed a dammed water body with a length of 200m, a width of 70m and a volume of about 30,000 m^3. The average gradient of the dammed ditch was 115‰. At present, the water body has flowed over the dammed embankment, forming a closure gap.

Fig.5 Deformation characteristics of the Boli landslide from July 14th to 19th

Causes and triggering factors of the Boli landslide

Geological disasters are the result of the coupling of endogenic and exogenic geological processes (Wang 2002). The endogenic geological processes are the foundation of geological disaster development, and the exogenic geological processes provide the necessary conditions for a geological disaster. The Boli landslide is the result of the resurrection of the ancient landslide deposits under the influence of the fragile geological environment and the steep slope topography with the combined action of precipitation and surface runoff.

Resurrection of the ancient landslide deposits

Under the influence of internal and external dynamics, a large-scale ancient landslide was developed in the Boli village. The "7.19" Boli landslide in Taozi Town, Yanyuan County was formed by the resurrection of a giant ancient landslide. An ancient landslide with an area of about 1.64km^2 is developed before the sliding. The ancient landslide deposits are mainly out of the sliding of the basalt weathering crust on the southeast side. The old landslide wall at the trailing edge of the landslide is obvious, and it is in the shape of a circular chair. The development of the ancient landslide is affected by the strong effect of the northeast-facing Maijiaping-Boli landslide, the freeze-thaw and moderate-strong earthquakes, with a thick weathering shell by sliding.

Geomorphology, lithology, and geological structures

The landslide area lies between the NE-strike faults of Woluo and Maijia with highly-developed secondary faults and crushed zone (Fig.6). The seismic activities in the study area is frequent. After the 1467 Ms 6.8 earthquake and the 1976 Ms 6.7 earthquake, an earthquake of magnitude 4.7 occurred around the landslide area on the 12th September, 2017. In term of the regional geomorphic characteristics, the study area is in the south segment of Hengduan Mountains area and belongs to middle and high mountains of scouring and erosion. The serious freeze-thaw, weathering and the tectonic movement cause a thick crust of weathering (over 30 m) in the study area. Due to the high proportion of farmland and serious deforestation in history, secondary forest exists within the watershed whose soil and water conservation property are considered less severe. The emergence stratum of landslide is mainly Emeishan basalt of Permian, Permian sandstone coal series of Leming group, Triassic sandstone of Qingtianbao group and argillaceous siltstone(Fig.6). The ancient landslides are piled up on the steeply inclined coal-bearing sandstone mud, forming slope condition conducive to landslide on the Permian Leping Formation sandstone coal-sediment strata, which have a northwest tendency and a dip angle of about 35°. As the slope of the base interface is steep, and the slope of the ancient landslide stack is about 25° on average, and the slope of the leading edge is more than 30°, the terrain meets the development of the landslide.

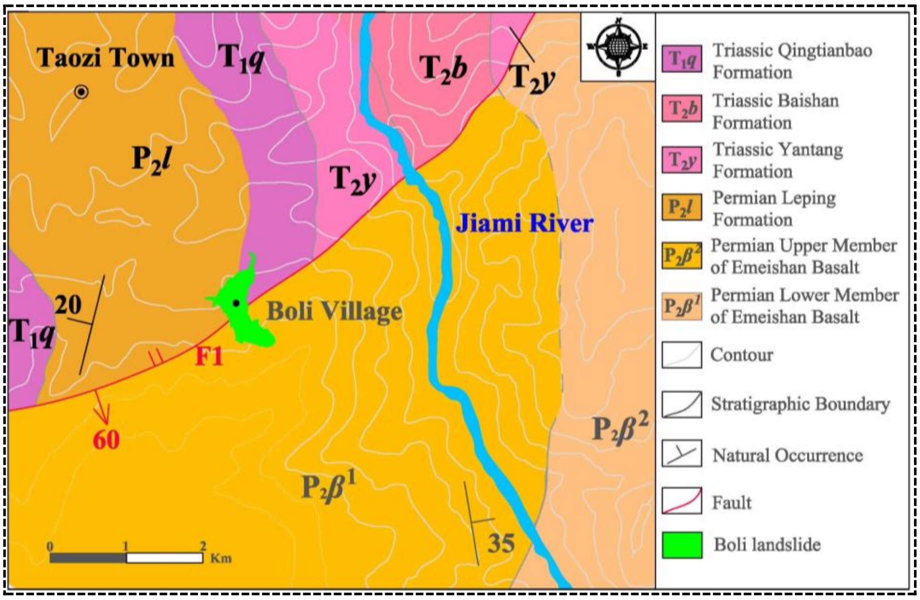

Fig.6 Geological map of the study area

Long-duration and low-intensity rainfall

The combined effect of long-duration, low-intensity rainfall and channel seepage drives the ancient landslides to form the Boli landslide (Fig.3 b). The study region frequently witnesses localised rainstorms. From July 13th to 19th, the landslide area continuously had long-duration and low-intensity rainfall(the cumulative rainfall was 159.5mm and the maximum hourly rain intensity reached 19.8mm). The monitoring data from the meteorological bureau of Yanyuan county shows that the average annual rainfall of the study area is 825.3mm and the maximum annual precipitation reaches 1113.4mm. There was the concentration of rainfall from April to October. According to the data from Figure 7, the cumulative rainfall of Taozi town between May 1st and July 18th was 817.4 mm in that period, which accounts for the 73 percent of the maximum annual precipitation. The value is notably higher than that in the corresponding period in recent years. In addition, the figure shows that the maximum daily rainfall in that period occurred on July 6 at 57.3mm. The rainfall lasted for 14 days preceding the landslide failure, with the total precipitation of 350.6mm. Besides that, moderate rain (with the daily rainfall over 10 mm) in Taozi town occurred 15 times during the one month before the event. Evidently, the landslide failure was not triggered by an intense rainfall of a single day, but rather with a prolonged as well as heavy precipitation process. The trailing edge of the ancient landslide deposits developed three regular water gullies. The ecological water holding capacity of the basin is affected by human activities. The direct seepage of rainfall and the infiltration of the trailing edge gully runoff made the soil of the old landslides loose and the soil body tended to be saturated, and the self-weight of the slope increased sharply. After the slip surface was formed along the basement interface, the landslide started as a whole.

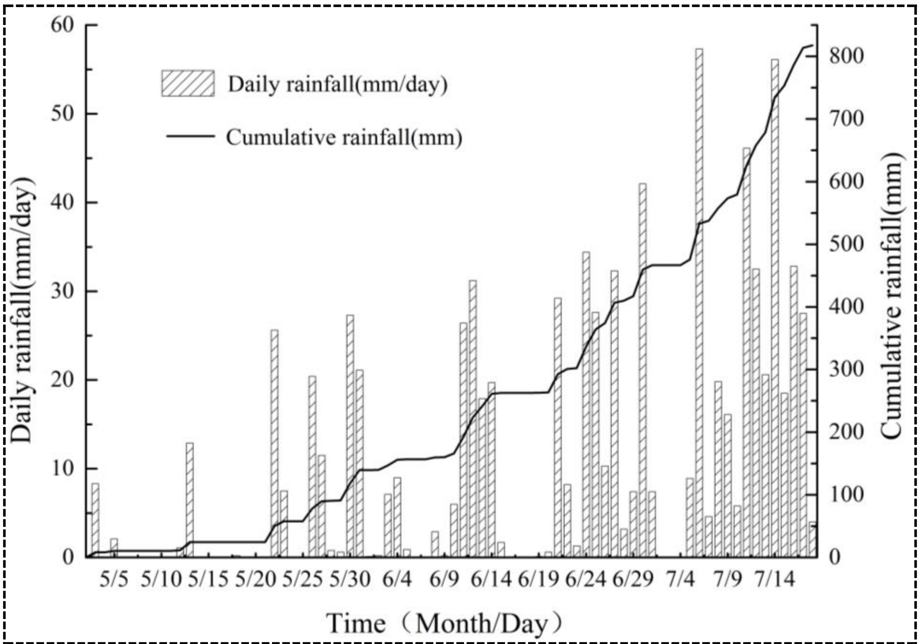

Fig.7 Daily rainfall (column charts) and cumulative rainfall (line charts) from May1st to July 18th, 2018

Failure mechanism of the Boli landslide

Creep sliping-tension cracking deformation along the deluvial layer in colluvial deposition

According to the analysis and experiment of the composition and structure of the slope materials in the source area (Table 2), the Boli landslide was located on the collapsed deposition and the weak layer was the interlayer that contained crushed clay in the collapsed slope. This kind of clay interlayer of the slope is common and forms a potential control surface (Yin et al. 2012). The test results showed that the sliding zone was in a fluid-plastic state and had low a shear strength. The cohesive force and the internal friction angle of the soil in the slide zone is found to be 12.05kPa and 19.8°, respectively. However, the original soil in the slip zone was undisturbed soil with certain structure and strength, and it contained gravels so its original shear strength was larger than the test result. Under the long-term effect of slope stress dominated by self-weight stress, the colluvial slope in the source area would slowly and persistently creep along the direction of the free surface.

Table 2 The test result of the physical and mechanical parameters of the landslide soils

Sampling point	Natural moisture content (%)	Natural density (g.cm^{-3})	Liquid limit (%)	Plastic limit (%)	Cohesive force (kPa)	Angle of internal friction (°)
Slip band soil	35	1.9	61.9	33.6	12.05	19.8

The Cohesive force (C) and Angle of internal friction（φ）can be calculated by referring to the inversion method in《Specification of Geological Investigation for Landslide Stabilization》（DZ/T0218-2006），which has been widely used in landslide stability analysis of water conservancy, transportation and railway departments in China. The following formula is used for inversion：

$$c = \frac{F\sum W_i \sin\alpha_i - \tan\phi \sum W_i \cos\alpha_i}{L} \quad (1)$$

$$\phi = \arctan\frac{F\sum W_i \sin\alpha_i - CL}{\sum W_i \cos\alpha_i} \quad (2)$$

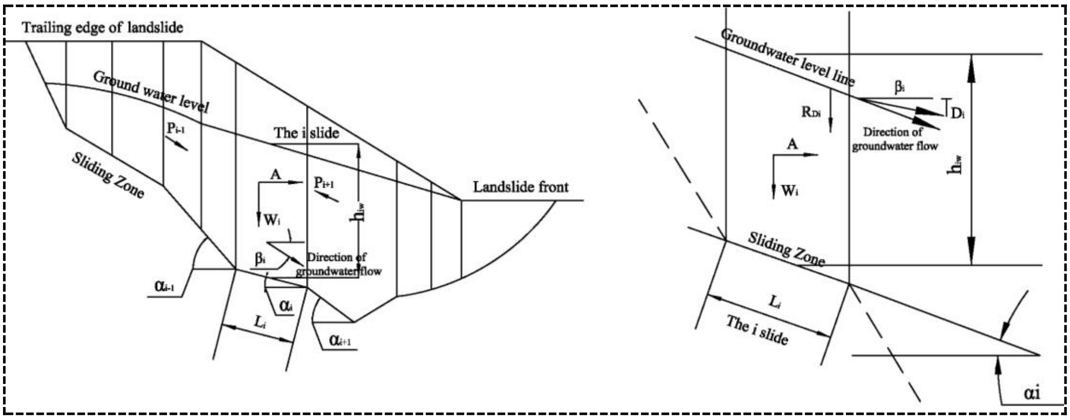

Fig.8 Calculation model of landslide: transfer coefficient method (folded linear sliding surface)

In the above formulas：c- Slide cohesion（kPa）；ϕ-Angle of internal friction on sliding surface（°）；W-The weight of the i（kN/m）；L-The length of the sliding surface (m); α_i -Slide Angle of i ；F-Stability factor (The landslide is in the state of integral temporary stability ~ deformation，F=1.05-1.00； The landslide is in the state of integral deformation ~ sliding, F=1.00-0.95)。

Under heavy rainfall conditions, when the stability coefficient of slope landslide is 0.98(unsteady state) for inversion, the above formula is used for inversion. The values of C and φ were found to be 9.27 kPa and 10.96° respectively. It is found that the Boli landslide is unstable through the comparison of C and φ values between the test and inverse calculation.

The continuous creep sliding of the slope causes the situation that the tensile stress gets concentrated at the trailing edge of the slope and the shear stress gets concentrated at the leading edge of the slope toe. Due to the high-angle unconformity interface between the gravel soil at the trailing edge of the slope and the weathered bedrock, the tensile fracture is gradually formed under the tensile stress. Although the gravel soil at the trailing edge of the slope has the characteristics of high porosity, loose structure and strong water permeability, mostly the surface layer is colluvial and viscous soil with fine particles, and the direct infiltration rate of surface precipitation is not high. Therefore, the formation of the tensile crack similar to a cutting trench in the trailing edge of the slope changed the infiltration path and capacity of the surface precipitation, and it is easier for the water to directly infiltrate into the interior of the slope. All these phenomena accelerated the speed of the creep sliding and aggravated the horizontal opening and vertical extension of the fracture in the trailing edge of the slide.

Fluidized trigger of landslide based on the diverse soil penetration

The rainwater quickly infiltrated into the slope because of the high permeability and the presence of the crack in the sliding trailing edge which permeated in the soil under the stress of self-gravity. Thus, the permeability of the rock mass gradually decreased from the trailing edge to the front edge of the slide and naturally it produced seepage pressure at the latter. The soil tended to be saturated, and the groundwater got collected at the front edge of the slope.

The SEEP/W software was used to simulate the change of the seepage field of the Boli landslide under rainfall conditions. The strata in the calculation range are distributed from top to bottom as the sliding body, the sliding zone and the bedrock. The horizontal width of the model is 2500m, the vertical height is approximately 600m, the total number of splitting units is 15,499, and the number of nodes is 15,865. In the analysis, the left, bottom and right boundaries of the model are defined as impervious. In addition, the other boundaries are set as potential infiltration boundaries. The soil prototype in the model is derived from the Boli landslide body. The upper part of the landslide body is mainly clay sand, and the lower part is mainly bedrock sandstone. The physical parameters of each layer in the numerical simulation are: natural moisture content of clay sand w=35%, density ρ=1.9g/cm^3, liquid limit W_L=61.9%, plastic limit W_P=33.6%. The hydraulic characteristics of the soil is Ks=0.01m/d, and the hydraulic parameters are determined by combining the functions in the SEEP/W function library with engineering experience. The rainfall intensity of 0.03m/d is used in the numerical simulation to analyze the change of the seepage field of the landslide in the entire slope. In order to facilitate the analysis of the pore water pressure (PWP) changes in the landslide during rainfall, we set up five pore water pressure monitoring points in the landslide body, four of which are located at the potential slip surface and one is located at the junction of the upper and lower soil layers (Fig. 4). The simulation results are shown in Figure 9 below.

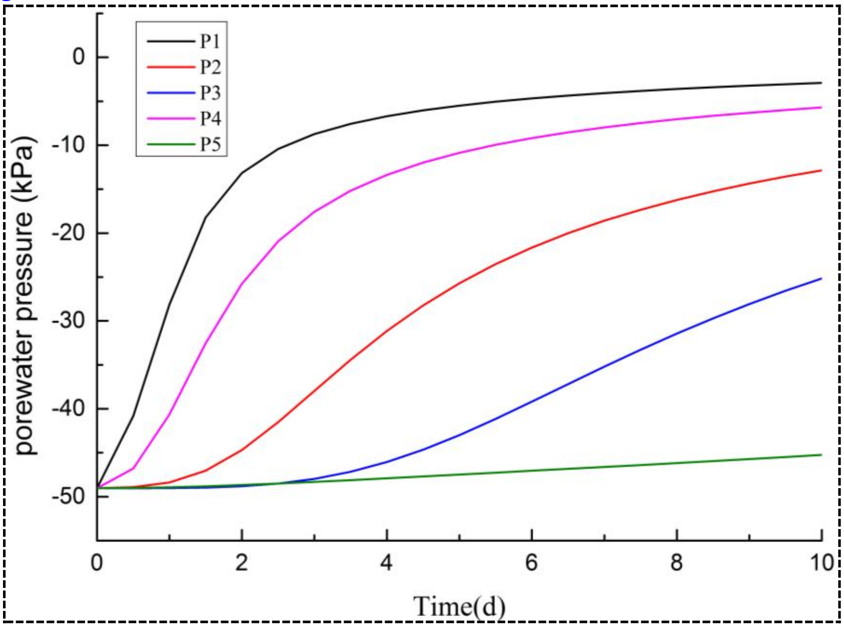

Fig.9 Variation of pore water pressure with time at different locations

It can be seen from the above figures that as the rainfall continues, the pore water pressure in the landslide increased at different rates. It indicates that the rainwater slowly infiltrated into the landslide, and the changes in the pore water pressure involved two processes: the rapid growth phase and the slow growth phase. In the former, the PWP increased faster during the first four rainy days and then later increased at a slower speed. Through the curves of the different PWP figures, it can be seen that the PWP of the upper and lower parts of the landslide body increase faster than those in other positions, and the PWP at P1 is larger than at other positions. It is worth mentioning that there are slight changes appearing in P5 located below the potential slip surface. It indicates that the rainwater did not penetrate into this position. It reflected that most of the water flowed along the surface of the potential slip in the landslide. It is consistent with the actual survey results and reflects the rationality of the seepage analysis model.

With the infiltration of rainwater, there was an increase of moisture content of the soil, and the pore water pressure of the soil on the potential sliding surface rose. When the shear stress approached or exceeded the shear strength, the soil approached into a shear failure state. The excess pore water pressure was formed and the overall average effective stress also decreased due to the reduction in the void ratio. Then soil liquefaction occurred and the local failure of the slope expanded rapidly and formed an accordant sliding surface. After the sliding, the natural moisture content (60%) of the soil in the sliding zone also approximated to its liquid limit (61.9%). Therefore, when the landslide is triggered, the soil mass in the front edge and sliding zone of the slope were basically in a fluid-plastic state and it also illustrated that the Boli landslide was triggered in the proximal fluidized state.

Real-time evacuation process and effect of the community based warning system

The real-time evacuation process of this landslide disaster is described as follows.

- On the afternoon of July 13, 2018, one household in Group 7 of the Boli Village was evacuated because of perceived landslide hazard danger.
- On July 14th, Mr Luo Zhiguo (38 years old), a villager of Group 7 in the village, reported that the house was cracked by 5cm, and the relevant landslide danger was reported to the group leader Mr Luo Shuangmo (47 years old). Mr Luo Shuangmo first went to the scene to check and verify the danger, and timely reported the situation to the Mr Tan Jiang(30 years old), deputy head of the Taozi Township, who is responsible for monitering geological disasters. Mr Tan Jian first reported the situation to Mr Deng Xianguo, deputy magistrate (42 years old) in charge of geological disasters in Yanyuan County. Mr Deng arranged Mr Wang Weidong (44 years old), deputy director of the County Land and Resources Bureau to organize relevant personnel to go to the scene to further investigate and verify the danger. Then they decided to evacuate all the 20 households of Group 7.
- On July 15, Mr Deng went to the scene to check the geological disaster progress and the temporary resettlement sites and arranged for Mr Luo Shuangmo to carry out further monitoring of the dangerous situation. Whereafter, he launched an emergency rescue plan and implemented emergency rescue funds of 40,000 RMB.
- On the morning of July 18, 4 people from the Yanyuan County Geological Environment Monitoring Station and the 281th team of the Sichuan Provincial Nuclear Industry Geology Bureau (Geological Disaster Technical Supports of Yanyuan County) rushed to the scene to investigate and found that the surface crack was about 30cm. After verifying the relevant danger, they decided to evacuate all the 45 households in Group 8 and 32 other households within the danger zone, and offered related relief materials such as tents.
- At about 8:40 pm on July 18, further verification and inventory of personnel evacuation were carried out to ensure the safe evacuation of the all relevant personnel.
- At about 5:40 in the morning of July 19, the landslide of the Boli Village slid as a whole. There were 65 families,186 houses in the Group 7 and Group 8, many roads, ditches, safe drinking water pipes and bridges in the Taozi Gully were completely destroyed.

From this successful real-time evacuation, we can summarize a response system that it is called the community based warning system for such disasters. Basic principles of the system mainly includes the following three aspects: 1)To take precautionary measures before the onset of a disaster; 2)To make the local population aware of how to escape when a disaster is pending; 3)To enable the community to carry out rescue operations themselves (Chen et al.2016). A community based warning system is simple, effective and scalable in response to such disasters in the mountains. There are four parts in the system: 1) A susceptible site is selected and is continuously monitored; 2) A system is built to convey information to the local people through warning boards, emergency notices and their local representative; 3)By various knowledge sharing sessions and the efforts of the disaster prevention office, the community has the information platform to connect with the monitoring system; 4)The rescue plan is pre-built and when a hazardous event occurs, local people can actively follow the rescue plan and save not only themselves but also other people (Fig. 10).

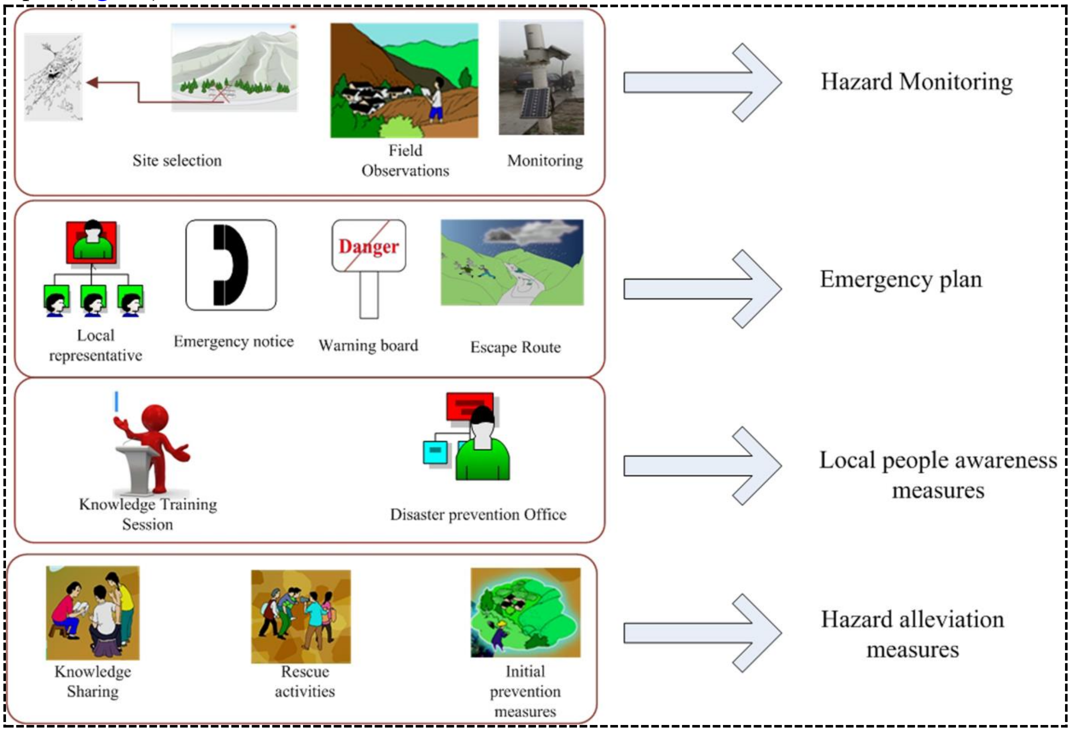

Fig. 10 Mode of community based warning: a step by step procedure

Discussion

In recent years, several catastrophic landslides have occurred in China (Huang 2009; Xu et al. 2010; Zhang and Yin 2013; Yin et al.2016; Yin et al. 2017). Among them, the Zhenxiong landslide (Yin et al. 2017), which affected the village of Zhaojiagou (Guozhu Town, Zhenxiong City, Yunnan Province) on January 11th, 2013, leaving 46 dead, had similar characteristics to the Boli landslide discussed in this paper. In both events, the source materials originated on mountain slopes at high elevations, in areas covered by dense vegetation. The Zhenxiong landslide and Boli landslide have not been identified by geological disaster risk assessment beforehand. Conventional geological hazard assessment based on in situ investigation is made difficult by the arduous topography in mountainous areas, thus the early detection and the implementation of precautional interventions are hardly feasible (Fan et al.2017). This is a widespread issue in the field of hazard prevention and mitigation in such areas (Korup 2005; Manconi et al.2016). Although the people from the Boli landslide have been successfully evacuated before the occurrence of the event, we should learn from the tough lessons of these catastrophic events and pay extreme attention to preventing and mitigating hazards. It is encouraged that the research community and the professional departments to focus their efforts into the following directions and practical actions:

(1) To strengthen scientific anticipation of regional geological disaster: It is necessary to invite the domestic and international renowned scientific research institutions in landslide and debris

flow to make a scientific estimate of such disasters considering the strong regional geological tectonic activities， freeze-thaw and weathering. Based on the indicators of the extreme precipitation, runoff-producing and flow concentration and the characteristics of ancient deposited landslide in recessed regions, the objectives of disaster reduction need to be scientifically determined further and previous investigation results should be checked again.

(2) Monitoring: early warning and emergency disposal should be enhanced to prevent and control the sudden geological hazards. The surveillance both of the residual loose deposits at the rear edge and the stability of landslide deposits should be strengthened. Besides that, dredging congested debris-flow accumulation body of Jiami River and draining away the dammed water of the upper reaches of landslide deposits are necessary to prevent the secondary disasters.

(3) To carry out integrated management of landslide and debris flow (taking watershed as units) considering the territorial development. We propose to compile landslide and debris flow exploration of the basin and to carry out design, construction and comprehensive treatment of disasters. In the treatment scheme, a landslide dam is designed to be in front of the landslide deposit and drainage canals are planned to be built behind the dam, with cultivated lands to be developed on both sides. The comprehensive treatment is going to be the exemplary program of geological disaster prevention, territorial development and integrated utilization in China.

(4) To intensify dissemination and recognition of risk avoiding work and extend the successful experience. In view of the huge social and economic benefits from it, we suggest generalizing the experience in disaster reduction provincially and nationally by publicizing relevant cases and commending the best practice.

Conclusions

This paper presents a preliminary investigation on the recent catastrophic Boli landslide. Based on visual interpretation of multi-temporal remote sensing images and field investigation, typical characteristics, deformation history, the cause and triggering factors of the Boli landslide were analyzed. Then, this paper tries to reveal the mechanism of the initiation of the Boli landslide through the analysis of physical and mechanical parameters of the landslide soil and SEEP/W model. Furthermore, real-time evacuation process was described in detail, and a community based warning system has been proposed. Therefore the following conclusions can be drawn.

1) The landslide could be divided into the push sliding part in the upper section and the tractive sliding in the lower section. The shape of the landslide is elongated in plane, and the main sliding direction of the landslide is between 320° and 345°, with $57\times10^4 m^2$ in area. The volume of landslide is 1800 million cubic meters, and is an oversize soil landslide.

2) The landslide was formed in two stages of creep deformation and sliding under the excitation of precipitation and channel seepage. The creep deformation stage occurred from July 14th to 18 th. The sliding phase lasted for about tens of seconds, and the slip mass was deposited in the Taozi Gully with a length of about 1000m.

3) The occurrence of the landslide has been shown to be the result of a combination of the

resurrection of the ancient landslide deposits under the influence of the fragile geological environment and the steep slope topography with the combined action of precipitation and surface runoff. It can be found that the Boli landslide is unstable through the comparison of C and φ values between the test and inverse calculation.

4) The failure of the landslide is mainly divided into two processes: creep sliping-tension cracking deformation along the deluvial layer in colluvial deposition and the fluidized trigger of the landslide based on the diverse soil penetration.

5) Early recognition of potential instabilities in mountainous areas is hardly feasible through conventional geological hazard assessment based on in situ investigation. Nevertheless, this case study showed that the use of a community based warning system and the collaborative work of experts and professionals can be successful in identifying potential hazards and performing quick assessments.

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References

Allstadt K (2013) Extracting source characteristics and dynamics of the August 2010 Mount Meager landslide from broadband seismograms. J Geophys Res Earth Surf 118(3):1472–1490. https://doi.org/10.1002/jgrf.20110

Chen NS, Tanoli JI, Hu GS, Yang CL, Ding HT, He N, Wang T (2016) Outlining a stepwise, multi-parameter debris flow monitoring and warning system: an example of application in Aizi Valley, China. Journal of Mountain Science 13(9):1527-1543. https://doi.org/10.1007/s11629-015-3624-5

Fan X, Xu Q, Scaringi G, Dai L, Li W, Dong X, Zhu X, Pei X, Dai K, Havenith HB (2017) Failure mechanism and kinematics of the deadly June 24th 2017 Xinmo landslide, Maoxian, Sichuan, China. Landslides 14:1229-2146. https://doi.org/10.1007/s10346-017-0907-7

Huang R (2009) Some catastrophic landslides since the twentieth century in the southwest of China. Landslides 6(1):69–81. https://doi.org/10.1007/s10346-009-0142-y

Korup O (2005) Large landslides and their effect on sediment flux in South Westland, New Zealand. Earth Surf Process Landf 30:305–323. https://doi.org/10.1002/esp.1143

Manconi A, Picozzi M, Coviello V, De Santis F, Elia L (2016) Real-time detection, location, and characterization of rockslides using broadband regional seismic networks. Geophys Res Lett 43:6960–6967. https://doi.org/10.1002/2016GL069572

Tian B, et al. (2017) Mapping Thermokarst Lakes on the Qinghai–Tibet plateau using nonlocal active contours in Chinese GaoFen-2 multispectral imagery. IEEE Journal of selected topics in Applied Earth Observations and Remote Sensing. https://doi.org/10.1109/JSTARS.2017.2666787

Wang SJ (2002) Coupling of Earth's Endogenic and Exogenic Geological Processes and Origins on Serious Geological Disasters. Journal of Engineering Geology 10(2):115-117. (in Chinese)

Xu Q, Fan X, Huang R, Yin Y, Hou S, Dong X, Tang M (2010) A catastrophic rockslide-debris flow in Wulong, Chongqing, China in 2009: background, characterization, and causes. Landslides 7(1):75–87. https://doi.org/10.1007/s10346-009-0179-y

Yin Y, Cheng Y, Liang J, Wang W (2016) Heavy-rainfall-induced catastrophic rockslide-debris flow at Sanxicun, Dujiangyan, after the Wenchuan Ms 8.0 earthquake. Landslides 13(1):9–23. https://doi.org/10.1007/s10346-015-0554-9

Yin Y, Xing A, Wang G, Feng Z, Li B, Jiang Y (2017) Experimental and numerical investigations of a catastrophic long-runout landslide in Zhenxiong, Yunnan, southwestern China. Landslides 14:649–659. https://doi.org/ 10.1007/s10346-016-0729-z

Yin ZQ, Wei G, Tang YG (2012) Characteristics of multi-model grain size distribution of slip surface soils and deposits of landslides. Journal of Engineering Geology 20(6) : 998-1006.(in Chinese)

Zhang D, Wang G, Yang T, Zhang M, Chen S, Zhang F (2013) Satellite remote sensing based detection of the deformation of a reservoir bank slope in Laxiwa Hydropower Station, China. Landslides 10(2):231–238. https://doi.org/10.1007/s10346-012-0378-9

Zhang M, Yin Y (2013) Dynamics, mobility-controlling factors and transport mechanisms of rapid long-runout rock avalanches in China. Eng Geol 167(12):37–58. https://doi.org/10.1016/j.enggeo.2013.10.010